Effect of Handle Design on Movement Dynamics and Muscle Co-activation in a Wrist Flexion Task

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ABSTRACT

Arm and wrist manipulanda are commonly used as input devices in teleoperation and gaming applications, establish a physical interface to patients in several rehabilitation robots, and are applied as advanced research tools in biomechanics and neuroscience. Despite the fact that the physical interface, i.e. the handle through which the wrist/hand is attached to the manipulator, may influence interaction and movement behavior, the effects of handle design on these parameters has received little attention. Yet, a poor handle design might lead to overexertion and altered movement dynamics, or result in misinterpretation of results in research studies. In this study, twelve healthy subjects performed repetitions of a wrist flexion task against a dynamic load generated by a 1-DOF robotic wrist manipulandum. Three different handle designs were qualitatively and quantitatively evaluated based on wrist movement kinematics and dynamics, patterns of finger and wrist muscle activity, and ergonomics criteria such as perceived comfort and fatigue. The three proposed designs were

further compared to a conventional joystick-like handle. Task performance as well as kinematic and kinetic parameters were found to be unaffected by handle design. Nevertheless, differences were found in perceived task difficulty, comfort and levels of muscle activation of wrist and finger muscles, with significantly higher muscle activation when using a joystick-like design, where the handle is completely enclosed by the hand. Comfort was rated high for the flat handle, adapted to the natural curvature of the hand with the fingers extended. These results may inform for the design of handles serving as physical interface in teleoperation applications, robot-assisted rehabilitation and biomechanics/neuroscience research.

Abbreviations:

Degree-of-freedom (DOF), electromyography (EMG), M. Flexor Carpi Radialis (FCR), M. Extensor Carpi Radialis (ECR), M. Flexor Digitorum Superficialis (FDS) and M. Extensor Digitorum Communis (EDC), co-activation index (CI), maximal voluntary contraction (MVC)

1. INTRODUCTION

Physical human-machine interaction is a field of growing importance, with applications in teleoperation, gaming, robot-assisted rehabilitation and sensorimotor control research. With the ability to precisely track movement trajectories and render virtual dynamics in well-controlled and reproducible conditions, robotic devices are well-suited for the investigation of the mechanisms underlying human sensorimotor learning and control, or (neuro)mechanical joint properties [1] and find application as therapeutic tools in neurorehabilitation. In research, single-degree-of-freedom (DOF) manipulanda have been widely used to evaluate passive and active joint properties, typically at the level of the wrist, by applying external, well-controlled perturbations to the joint [2, 3]. More complex planar robotic manipulanda have allowed new insights into learning and adaptation processes of the central nervous system during reaching movements in stable or unstable force fields generated by the robot [4, 5]. Although there have been approaches to quantify hand-handle interaction forces [6], other aspects such as handle ergonomics are also important as it has been shown that handle design can strongly influence performance as well as movement dynamics and kinematics during manipulation tasks [7-11]. Motivated by the ergonomics of hand-held machine tools, several studies have looked into optimizing cylindrically shaped handles, and found that the handle diameter influences forearm muscle activity, force generation capabilities, as well as perceived comfort during power grip tasks [12-15]. However, in the case of isolated wrist tasks, there is less information on how handles should be designed and how the finger placement and guidance imposed by the handle might influence subjects' performance as well as affect comfort and fatigue. Yet, the wrist joint is ideally suited for motor learning experiments as, through an appropriate fixation, it can be reduced to a mostly 1-DOF joint with a large range of motion (up to 95°/98° [male/female] flexion), capable of generating high torques (around 8.6 Nm for males and 5.2Nm for females in isokinetic contraction, [16]) during dynamic interactions.

Most of the existing wrist robots used in motor learning research or in neurorehabilitation were designed with joystick-like handles [17-19], in which the subject holds a cylinder-shaped handle using a power grasp, and the hand can enclose the entire handle surface. Pilot data previously collected by our group during dynamic wrist flexion tasks with a joystick-like handle mounted on a robotic wrist manipulandum (ReFlex, [20]) illustrated that such a handle may lead to high co-contraction levels between wrist flexor and extensor and between finger flexor and extensor muscle groups, which might affect the observation of adaptation mechanisms during motor learning experiments, and increase muscle fatigue or muscular pain during successive task repetitions. This might be an undesired side effect, especially in tasks involving intensive interaction with a robotic manipulandum, such as during robot-assisted rehabilitation.

An ergonomic interface between a robotic manipulandum and the wrist should in general consider several biomechanical and physiological factors. For example for the investigation of wrist joint control, it is desirable that movements are controlled mainly by wrist muscles and the contribution of extrinsic finger muscles is minimized. Mechanically unstable loading – e.g., caused by awkward postures due to ergonomically inadequate devices – may restrain or alter the formation of optimized patterns of muscle activity that occur during motor adaptation [21, 22], leading to increased co-activation or co-contraction (i.e. co-activation of an agonist-antagonist muscle pair) of the forearm muscles [3]. High rates of co-contraction and co-activation affect joint impedance [23] and may result in higher rates of fatigue, possible overexertion and development of muscle pain [24, 25]. As subjects are typically required to perform many movement repetitions during motor learning tasks involving novel dynamics or in rehabilitation applications, the development of muscle fatigue or muscular pain should be avoided. It is thus important to reduce excessive muscle activation through an ergonomic design.

In this study, we present the qualitative and quantitative evaluation of three handle designs, evaluated a 1-DOF robotic wrist manipulandum during repeated dynamic wrist flexion movements against a load generated by the robotic manipulandum. Handles are compared

using ergonomics criteria such as comfort, fatigue and pain evaluated through questionnaires, as well as an analysis of muscle activity patterns in wrist and hand muscle groups measured with surface electromyography (EMG). We further compare patterns of muscle activity for a joystick-like handle used in previous measurements with the manipulandum. In addition, wrist dynamics and performance in a target reaching wrist flexion task are analyzed. We hypothesized that handle design and finger position on the handle would influence the way subjects perform fast wrist flexion movements, generate wrist flexion torque, and modulate wrist impedance.

2. MATERIALS AND METHODS

2.1 *Subjects*

Twelve healthy subjects (age 27.8 ± 10.7 years, 7 males) were recruited for this study. Participants came to the Rehabilitation Engineering Laboratory at ETH Zurich for a one-hour session with the robotic manipulandum (ReFlex, [20]). As inclusion criteria, subjects had to be over 18 years old and right handed. Exclusion criteria were any neurological disorders, functional deficits of the wrist/hand as well as any history of wrist injury, or presence of any dermatological diseases.

Prior to the experiment, each participant was informed about the details of the protocol and gave informed written consent. The study was approved by the ETH Zurich Ethics Commission (EK 2010-N-18).

2.2 *Apparatus*

A 1-DOF robotic manipulandum designed for the investigation of the wrist joint (ReFlex, Figure 1) was used to evaluate the different handle designs. It can precisely control, assess and perturb wrist movement in flexion and extension under dynamic or isometric experimental conditions [20]. Thanks to its hybrid actuation system composed of a brushed

DC torque motor (RE65, Maxon Motor, Sachseln, Switzerland) and a magnetic particle brake (S90MPA-B34D50H38, Stock Drive products/Sterling Instruments, New Hyde Park, NY, U.S.A.) connected in parallel over a timing belt transmission, the manipulandum can safely render a wide dynamic range of mechanical impedance and torque. Angular position of the handle is measured with a high-resolution optical encoder fixed directly to the motor shaft (R158, 1'000'000 counts/rev, Gurley Precision Instruments, Troy, NY, U.S.A) to allow for a high velocity resolution (0.36 deg/s) at high sampling rate (1kHz). Redundant position sensing is performed at the level of the brake using a rotary potentiometer (GL 60, Contelec AG, Biel, Switzerland) for safety purposes. A 6-DOF force/torque sensor (Mini45, ATI Industrial Automation, Apex, NC, U.S.A.) is mounted between the handle support and the motor shaft to monitor the wrist torque applied by the subject and compensate for the apparent dynamics of the manipulandum. During dynamic wrist flexion and extension, force and torque data are monitored to assure that the current task is performed correctly, with minimal compensatory force and torque in directions transverse to the movement under investigation. The manipulandum is controlled using 2 personal computers, i.e. a standard host PC running Windows 7 with LabVIEW 2011 (National Instruments, Austin, TX, U.S.A.) for the user interface and visual display, and a target PC running LabVIEW RealTime 11.0 (National Instruments, Austin, TX, U.S.A.) for robot control. The real-time control system runs at a sampling frequency of 1 kHz.

2.3 Handles

Handles are mounted to the robotic manipulandum through a rectangular aluminum base plate (70x80 mm²) that can be shifted longitudinally to adapt to the user's arm length and to assure that the axis of rotation of the wrist is aligned with that of the motor shaft. The handles were formed from a sheet of thermoplastic material (Synergy Plain Blue Sheet, Sammons Preston, Bolingbrook, IL, U.S.A.) adapted to the shape of a middle size hand (hand length 193mm, palm length 114mm, hand breadth 88mm, hand thickness 32mm [26]), which is attached to the aluminum base plate on the palm side of the hand using rigid foam (50% Pedilen® rigid foam 300, 50% Hardener for Pedilen rigid foams, Otto Bock Suisse AG,

Luzern, Switzerland). The design of the three handles used in this study (described below) was motivated by ergonomics and biomechanical considerations as well as based on a review of existing robotic devices used in physical human-robot interaction studies [17-19, 27-29]. In addition to the three investigated handles, a fourth handle used in previous measurements served as reference for the EMG analysis.

2.3.1 Curved handle

With the curved handle the hand is placed in a natural position, with the fingers II to V in adduction [27, 28]. (Figure 2, A). The thermoplastic sheet reaches 0.5 cm over the fingertips on one side, and ends 1 cm before the wrist joint on the other (for the middle size hand described above). The metacarpophalangeal joints are held in a 10° flexed position. The thumb is supported by a plate and is placed in a 45° abducted position. Furthermore, the handle is curved at the bottom to support the hand. A Velcro® strap runs over the metacarpophalangeal joints of fingers II-V.

2.3.2 Grooved handle

The grooved handle is designed to minimize the torque produced by the fingers during wrist tasks. The handle is adapted to a splayed hand in order to immobilize the fingers during wrist movements [20], and to follow the natural curvature of the palm, reaching from the intermediate phalange of the middle finger up to 1 cm before the wrist joint (Figure 2, B, C). The thermoplastic sheet is adapted to the inside of the hand and has 4 escaping grooves which maintain the 4 fingers (i.e. index finger to little finger) in a position of 10° flexion and 20° abduction. The thumb is also guided within a groove in a 25° abducted position. To assure that the hand is firmly fixed to the handle, 2 padded Velcro® straps are placed over the dorsal side of the hand.

2.3.3 Palm handle

The palm handle is similar to a joystick-like handle where subjects can partly flex the fingers around a cylinder of 35mm diameter [17-19] (Figure 2, D, E). To minimize co-contraction in finger muscles and prevent subjects from tightly grasping the handle during wrist tasks, two piezoresistive force sensors (Flexi Force ®-Model # A201 (0-110N), Tekscan Inc., South Boston, MA, U.S.A.) are fixed on the backside of the handle to monitor the finger force applied by the subject. In case a finger force above 2N is detected, a signal is given, requiring the subject to release the grip on the handle. This step was motivated by pilot data, previously collected with a standard joystick-like handle (Figure 2, F), where high levels of co-contraction for antagonistic muscle pairs at the level of the wrist and the fingers were observed in most subjects. Again, the thermoplastic sheet is cut 1 cm before the wrist joint in order to assure that the handle does not interfere with the flexion of the wrist. The thumb is positioned in 35° abduction, and the handle is curved at the bottom to support the hand. Again two Velcro® straps placed over the dorsal aspect of the hand are used to fix the hand to the handle.

2.4 Wrist flexion task

To evaluate the three handles in the context of a representative and well-defined dynamic wrist task, a point-to-point target-reaching paradigm [30] was implemented. This task was selected as it is a commonly employed motor learning task that is challenging and demanding, in which, due to the high number of repetitions, comfort and fatigue might play a non-negligible role. Subjects were asked to perform a succession of fast and precise target reaching movements, from a starting position of $0 \pm 0.5^\circ$ wrist flexion to an end position of 30° wrist flexion. Start and end positions were represented by two circles displayed on a monitor placed in front of the subject (Figure 1, A). Visual feedback of the measured angular position of the wrist was further represented by a moving ball coupled through a lever to a virtual center of rotation. A window of $\pm 2^\circ$ was given for the successful reaching of the target

position. In addition, the movement time was constrained to a short window of 400 ± 50 ms to assure a mostly feed forward control. Subjects had to initiate the movement within a given time window of 550 ms, indicated by an acoustic countdown. During the wrist flexion movement, a resistive, velocity-dependent force was generated by the motor (equation 1),

$$\tau_n(t) = D * \dot{\varphi}(t) \quad (1)$$

with τ_n the torque applied by the motor and $\dot{\varphi}$ the angular velocity of the wrist. The damping coefficient of $D=0.011$ Nms/deg was empirically chosen in order to achieve a noticeable effect on the task dynamics. After each trial, corresponding to one target reaching movement, a qualitative feedback of the performance was displayed on the monitor. This feedback was based on the end-point error and reaching duration (target missed, too slow, too fast, early start, late start, good job). Both precision and time constraints had to be met in order for a trial to be considered successful. After the completion of the trial, subjects were asked to return the wrist to the initial angle, without any resistance from the robot, in order to initiate the next trial.

2.5 Protocol

A session was composed of 3 experimental blocks consisting of 100 trials to evaluate each of the handles. To avoid ordering effects, an individual sequence was pseudo-randomly determined for each subject prior to the experiment. Subjects were then informed about the experimental procedure and the use of the robotic device and its safety systems. Ag/AgCl surface EMG electrodes (Blue Sensor N, Ambu®, Ballerup, Denmark) were placed on wrist and finger muscles M. Flexor Carpi Radialis (FCR), M. Extensor Carpi Radialis (ECR), M. Flexor Digitorum Superficialis (FDS) and M. Extensor Digitorum Communis (EDC). Electrodes were positioned on the belly of each muscle and were individually checked for good placement before starting the measurement. The electrodes were connected to wireless amplifiers (Telemyo DTS System, Noraxon, Scottsdale, AZ, U.S.A.) streaming data to a separate desktop computer synchronized with the real-time target computer of the

ReFlex through a TTL trigger pulse. The EMG data were sampled at 1.5 kHz. After placing the electrodes, three reference measurements were made to determine the maximal voluntary contraction (MVC) of each muscle through isometric contractions against a rigid and grounded object. The highest activation level over all measurements for each muscle was taken as MVC. The subject's arm was then installed in the device. Proper alignment between the wrist joint axis and the motor shaft was verified through visual inspection. Four padded supports located at the level of the elbow and distal part of the forearm were used to maintain the arm in proper position (Figure 1, A). The height of the robot was adjusted so that the elbow was in 35° flexion, the upper body was vertical and the shoulder was in 30° abduction at rest position. Once installed, a detailed explanation of the visual feedback was given, with the possibility for subjects to perform several test trials before starting the first experimental block. Between the blocks, a break of 5 minutes was given, during which the next handle was installed and aligned with the subject's hand. At the end of each block, subjects filled in a questionnaire, in which they were asked to rate handle comfort (0 = "uncomfortable", 10 = "comfortable"), task difficulty (0 = "very easy", 10 = "very difficult") and wrist fatigue (0 = "no fatigue", 10 = "severe fatigue") on 11-point numeric rating scales adapted from McDowell and Newell [31]. After completing the 3 blocks, subjects were asked to name their favorite handle (only one selection was possible), and indicate whether they felt any pain or discomfort (0 = "no pain", 10 = "severe pain", and if yes with which handle) throughout the entire session on a similar numeric rating scale[32]. Overall, a measurement session lasted about two hours.

2.6 Outcome measures and statistical analysis

Position and force/torque data were sampled at a frequency of 1 kHz. The velocity estimate and the wrist flexion torque signals were filtered using a 2nd order Butterworth lowpass filter with a cutoff frequency at 20 Hz. This cutoff frequency was chosen as the bandwidth of human movements is typically below 10 Hz [33]. In addition to position, velocity estimate and

torque data, trial success/failure information was stored. For each trial, the part corresponding to the wrist movement was identified using position (starting position) and velocity thresholds (2 deg/s) , then normalized over movement duration for averaging. The analysis of average trajectories for the successful trials of each experimental block was performed with MATLAB R2011a (The MathWorks, Natick, MA, U.S.A.), calculating a cross-correlation coefficient (R) between the average trajectory and a minimum jerk trajectory computed from the initial angle to the target angle [34]. A minimum jerk trajectory was selected as reference trajectory as it is representative of fast and smooth target reaching movements in humans [35, 36].

EMG signals were post processed using commercial software (Myo Research XP 1.08.16, Noraxon, Scottsdale, AZ, U.S.A.). The signals were rectified and the root mean square (RMS) over a 50 ms (75 data points) sliding window was calculated. EMG signals were normalized with respect to the MVC, and signals from each trial were normalized over time. Based on these signals, a co-activation index (CI) was calculated between relevant muscle pairs (FCR-ECR, FCR-FDS, ECR-EDC, FDS-EDC), using the following method (adapted from [37]):

$$CI = \frac{1}{n} \sum_{t=1}^n \frac{\min(EMG_{1,t}, EMG_{2,t})}{EMG_{1,t} + EMG_{2,t}} \quad (2)$$

where $EMG_{1,t}$ and $EMG_{2,t}$ are the rectified muscle activity amplitude for the two muscles being compared at the time point t . The CI values were calculated for three different sections of the movement: i) the entire trial, ii) at the beginning of the movement (10-30% of the movement) where subjects accelerated the wrist against the resistive, velocity-dependent force field and iii) at the end (70-90%) where the subjects had to stabilize the end point position. Additionally, the maximal and the average normalized muscle activity were calculated for the four muscles FCR, ECR, FDS and EDC over each the three different sections of the movement.

Statistical analysis was performed with SPSS Statistics 20 (IBM Corporation, Armonk, NY, USA). Repeated measures ANOVAs and post-hoc tests with Bonferroni correction were used, as data was normally distributed (first assessed using Kolmogorov-Smirnov tests). For the comparison between CI values of the three tested handles and the joystick-like handle used in previous measurements, using the same wrist task but within a different study (5 subjects), an unpaired t-test was used. For all tests the significance level was set to $\alpha=0.05$.

3. RESULTS

3.1 *Task performance and wrist dynamics*

The percentage of successfully accomplished trials (i.e. reaching the target position within the given time and accuracy constraints) over all subjects are presented in Figure 3 (A). The percentage of successful trials was not influenced by the choice of the handle ($F(2,22)=0.321$; $p=0.728$). Average movement trajectories, corresponding angular velocity and wrist torque profiles calculated from the successful trials are shown in Figure 3 (B-D) for the three handles used in this study. High correlations with a minimum jerk reference trajectory were found for each handle (curved handle: $R=0.998$, $p<0.01$; grooved handle: $R=0.997$, $p<0.01$; palm handle: $R=0.997$, $p<0.01$). Note that success rates remained relatively low for each handle (between 11-64% for a single block), illustrating the difficulty to achieve the dynamic wrist target-reaching task within the imposed time and accuracy constraints.

3.2 *Patterns of muscle activity*

Surface EMG signals obtained from the 4 forearm muscles (i.e. FCR, ECR, FDS and EDC), for all successful trials of a representative subject are shown in Figure 4 (A). These trials were performed with the palm handle and show the activation pattern of flexor muscles during the first phase of the movement (FCR, FDS), as well as a time-dependent activation shift of the extensor muscles in the later phase of the movement (ECR, EDC). The corresponding heat maps for the relatively low co-activated muscle pair FCR-ECR and for

the highly co-activated muscle pair FCR-FDS are presented in Figure 4 (B) and Figure 4 (C), respectively.

Averaged co-activation indices calculated for muscle pairs formed between FCR, ECR, FDS and EDC are presented in Figure 5 for each handle. Only the two antagonistic muscle pairs (co-contraction) FCR-ECR and FDS-EDC and the two synergistic muscle pairs (co-activation) FCR-FDS and ECR-EDC were investigated, as the muscle pairs FCR-EDC and ECR-FDS are not relevant from an anatomical standpoint. Only nine subjects could be included in this analysis due to the presence of corrupted EMG-signals in part of the experiment for the other 3 subjects.

The overview of the repeated measure ANOVAs for the CI values are presented in Table 1. The statistical analysis of CI-values for the muscle pair FCR-ECR showed only a significant within-subject effect when analyzing the entire trial ($p < 0.05$). The post-hoc analysis showed only a significantly higher CI value for the grooved handle compared to the palm handle. A significant within-subject effect was also found for the muscle pair FCR-FDS for the entire trial ($p < 0.05$) as well as for the sub-part from 10-30% of the movement ($p < 0.05$). Despite the significant effects found in the within-subject tests the pairwise comparison did only survive the Bonferroni correction for the latter where the curved handle had a significantly higher CI value compared to the palm handle ($p < 0.05$). The statistical analysis of the CI-values comparing the three investigated handles and the joystick-like handle is presented in the lower part of Table 1.

The statistical analysis of the mean and maximal EMG values of the four muscles showed no significant difference between the three investigated handles for any of the analyzed trial parts. The mean and the maximal values are presented in Figure 6 and the corresponding F-values and p-values are presented in Table 2. The statistical analyses of the mean and maximal EMG values between the joystick-like handle and the three investigated handle are presented at the bottom of Table 2.

3.3 *Ergonomics*

Results of the questionnaires for the twelve participants are summarized in Figure 7. All subjects rated the three handles to induce no pain (0 on a 0-10 scale) with repeated use, with the exception of two subjects, who stated that they felt slight pain (2 on a 0–10 scale) during the experiment with the grooved handle. In response to the question of which handle the participants rated as best for the evaluated wrist flexion task, the grooved handle was chosen 5 times, the curved handle 4 times and the palm handle 3 times. In terms of fatigue and pain the analysis of the different handles showed no significant differences (fatigue: $F(2,22)=0.809$, $p=0.458$, pain, with Greenhouse-Geisser adjustment for sphericity: $F(1,11)=2.200$, $p=0.166$).

Comfort, on the other hand, was influenced by the type of the handle ($F(2,22)=3.496$, $p<0.05$). The post-hoc analysis showed that subjects rated the palm handle significantly higher than the grooved handle ($p<0.05$). The other two pairs showed no statistical difference (grooved-curved: $p=0.087$, curved-palm: $p=0.601$). Similarly, the perceived task difficulty was significantly influenced by the handle type ($F(2,22)=3.476$, $p<0.05$). The pairwise analysis again showed a significantly higher perceived task difficulty for the grooved handle compared to the palm ($p<0.05$). The other two combinations again showed no significant difference (grooved-curved: $p=0.269$, curved-palm: $p=0.137$).

4. DISCUSSION

This paper presented the evaluation of three handle designs (i.e. curved handle, grooved handle and palm handle) to be used as interface between the hand and a robotic manipulandum during physical human-robot interaction. A study with 12 healthy subjects was performed with the objective of comparing the three handles in terms of movement dynamics and subjective ergonomic criteria such as fatigue, comfort and pain during repeated wrist flexion tasks. Additionally, patterns of muscle activity during this typical motor learning task

were further evaluated for the three handles and compared to a widely used joystick-like design [17-19].

4.1 Handle design does not influence performance in a wrist flexion task

The results of the present study suggest that the handle design did not influence subjects' performance in a dynamic wrist flexion task. All handles showed similar success rates for accomplished trials. An analysis of angular trajectories showed that, for all handles, successful reaching movements corresponded well to a minimum jerk profile, which is characteristic of natural feed-forward target reaching movements [36]. Wrist torque profiles were also found to be similar across all handles. Thus, despite different finger positions on the handles, subjects could perform wrist tasks equally well with all handles. Several studies have shown that handle design, e.g. the diameter of a cylindrical handle or lid, or the wrist posture, affected by the handle design, influences variables such as maximal force and torque production at the level of the fingers and the wrist [38-42]. However, in the presented study the required wrist torque never exceeded 1.8 Nm, which is less than 40% of maximum voluntary wrist torque. Our results indicate that for this torque range the handle design has only limited to no impact on dynamic performance when the wrist is primarily involved in the task. Additionally, the similar subject performance with the three investigated handles might be explained by the fact that subjects could still learn to perform the dynamic task, despite a sub-optimal or uncomfortable interface.

4.2 Handle design influences muscle co-activation

Patterns of muscle activity during wrist flexion tasks were found to be similar across handles. Clear synergistic activation between wrist and finger flexors (FCR-FDS), and between wrist and finger extensors (ECR-EDC) were observed. This coupling can easily be explained by the wrist anatomy, as FCR and FDS both contribute to wrist flexion and ECR and EDC both

contribute to wrist extension [43]. FCR and FDS generated the torque against the velocity-dependent force field and accelerated the hand in the first phase of the task. ECR and EDC were maximally activated at the end of the movement to slow down the hand and stabilize the end-point position. In general, the comparison between the antagonistic wrist muscle pair FCR-ECR and the antagonistic finger muscle pair FDS-EDC showed a time-dependent shift in activation of the respective agonist and antagonist muscles, resulting in low CI values. With the grooved handle, a significantly higher co-contraction of the wrist muscles (FCR, ECR) was observed compared to the palm handle. This might be caused by the specific shape of the grooved handle (i.e. with the fingers are maintained in an abducted position) that required subjects to perform the task with more activation of the ECR muscle. A significant difference in co-activation index was also found between curved handle and palm handle at the beginning of the movement for the muscle pair FCR-FDS. The higher co-activation index might be caused by the fact that the FCR and EDC muscles were similarly highly activated when using the curved handle even if FCR and EDC were by trend more highly activated when using the palm handle. It should be noted that a higher CI-value can result from a higher activation of the antagonistic muscle or from a lower activation value of the most active muscle. Interestingly, the agonist-antagonist co-activation was significantly lower for all three handles at the end of the trial compared to prior data collected with a joystick-like handle during the same dynamic wrist flexion task with the robot. With the joystick-like handle, subjects had the tendency to increase hand and wrist stiffness by tightly grasping the handle from the beginning of the movement. This was underlined by the mean and maximal EMG values recorded where all muscles were typically more active in each period of the movement when the joystick-like handle was used. While this may offer more stability during the movement, this non-task-related increase in wrist stiffness could alter endpoint impedance during motor tasks, and might lead to increased fatigue over time. With handles offering curved interaction surfaces, such as the curved handle, the fingers are in a more extended position, such that the ability to generate finger force against the handle is

decreased [14]. This limits finger muscle activity during the movement and allows to better isolate the contribution of wrist muscles to the task.

The complete absence of a physical support for the fingers when using the palm handle resulted in higher activity of the FDS muscle compared to the curved and the grooved handle. One would expect that, when freely moveable, fingers need to be stabilized. The stabilization of fingers could occur through increased joint stiffness, which should also result in a higher antagonistic activation of the EDC muscle. Interestingly, a higher EDC activation during the use of the palm handle was not seen. This would suggest that, with the palm handle, fingers are not stabilized by increased joint stiffness but rather through establishing contact of the proximal phalanges with the handle. Thus, despite the statistically significant differences in some of the reported EMG outcomes, the handle design seems to influence the muscle activity patterns only marginally.

4.3 Subjective feedback from questionnaires

Comfort was rated relatively high ($>6.6/10$) for all three handles. The results showed that the grooved handle was significantly less comfortable than the palm handle, and two subjects further reported minor pain while using the grooved handle. This might be due to the fact that for participants with small hands, it was difficult to fit the little finger into the designated groove. This underlines that grooved handles or, in general, handles that guided fingers into predefined positions should be customized to each individual subject, which might be a drawback. The level of fatigue reported by subjects was low, with no statistically significant difference between handles. Note that a quantitative fatigue analysis based on the EMG data [44, 45] was not implementable here, as muscles were not continuously activated during single trials.

4.4 Limitations

The outcomes of this study are limited by the relatively low number of subjects. Furthermore, the reported fatigue and comfort may have been influenced by the relatively long duration of each block (15 minutes) and the repetitions of blocks on a single day. The experiment was

439 limited to a single dynamic target-reaching task in wrist flexion, and the results might
440 therefore not translate to other tasks.

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5. CONCLUSIONS AND FUTURE WORK

The results of this study point at a very important component in physical human-robot interaction, which often receives only limited consideration. While robotic manipulanda are being developed for a variety of applications, it is crucial to evaluate how the design of the physical interface between the robot and the human can influence ergonomics and sensorimotor behavior. Our results from a wrist flexion task suggest that joystick-like handles lead to increased co-contraction at the level of the wrist and the fingers, especially for the two extensors ECR and EDC. While such handles might be ideal for planar manipulanda, where higher wrist stiffness might be beneficial to increase stability during arm movements, they should be avoided in devices dedicated to the study of wrist tasks. Robotic manipulanda interacting with the wrist joint for repeated flexion tasks should rather consider using a handle that is fixed on the palmar side of the hand with a rigid surface adapted to the anatomy of the hand. The use of a handle where the fingers can be freely moved may result in increased involuntary activation of the FDS muscle. This should be especially considered when investigating activation patterns of muscles running over multiple joints. For the wrist task presented in this study, both the proposed curved handle and palm handle were found to be suitable and will thus be used in future motor learning experiments. In general, all three handles lead to similar kinematic and kinetic parameters as well as task performance. However, a handle in which fingers are constrained, like the grooved handle presented in this study, is not advisable, as it might cause light pain if not adjusted to the anthropometry of the individual subjects' hand. Further, the palm handle was associated with increased FDS activity, thus it should not be used in studies where this is relevant, e.g. to investigate wrist impedance. In conclusion, we recommend using the curved handle for such tasks, as it is the most versatile and universal option.

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591 Figure 1: Haptic wrist interface ReFlex. Experimental setup during a measurement session
592 including the visual feedback presented to the subject (A). Front view of the adjustable arm
593 support with a curved handle (B).

594

595 Figure 2: The different handles used during the experiment. The curved handle adapted to
596 the natural curvature of the hand (A), the grooved handle with the fingers II to V in abducted
597 position (B,C), the palm handle in which subjects were not allowed to flex the fingers around
598 the handle (D,E) and the joystick-like handle used in previous experiment (F), in which finger
599 flexion was not prevented.

600

601 Figure 3: The boxplot represents the percentage of successful trials with the median
602 presented as black line, the single data points presented as black points and the mean
603 presented as colored line (A). The repeated measures ANOVA showed no significant
604 difference between the investigated handles. In addition the averaged movement trajectories
605 during successful trials of all subjects are presented (B). The minimum jerk trajectory
606 computed between initial and target angular position serves as reference for a fast and
607 smooth target reaching task. The corresponding torque (C) and velocity (D) profiles are
608 additionally presented at the bottom part.

609 Figure 4: Mean EMG activation pattern (only successful trials) of one representative subject.
610 Means of the four muscles Flexor Carpi Radialis (FCR), Extensor Carpi Radialis (ECR),
611 Flexor Digitorum Superficialis (FDS) and Extensor Digitorum Communis (EDC) are shown in
612 black and the standard deviation areas in grey (A). The dashed at 0% illustrated the start of
613 the trials. Illustration of the co-activation showing the temporally shifted activation of both
614 antagonistic wrist muscles (B) and the simultaneous activation of both flexors FCR and FDS
615 contributing to wrist flexion (C). Dark areas are representative for a high number of data
616 points whereas bright areas stand for low number of data points.

617

618 Figure 5: Mean co-activation index (CI-values, n=9, mean $\pm$ SE) for the investigated handles
619 between four muscle pairs composed of Flexor Carpi Radialis (FCR), Extensor Carpi
620 Radialis (ECR), Flexor Digitorum Superficialis (FDS), Extensor Digitorum Communis (EDC)
621 during the complete trial (0-100%) the beginning of the trial (10-30%) and at the end of the
622 trial (70-90%). CI values obtained in a preliminary study performed with five subjects using a
623 joystick-like handle (black bar on the right for each muscle pair) are reported for comparison.
624 *p<0.05, **p<0.01.

625

626

627 Figure 6: Mean (dark) and maximum (bright) EMG values for the four muscles Flexor Carpi
628 Radialis (FCR), Extensor Carpi Radialis (ECR), Flexor Digitorum Superficialis (FDS) and
629 Extensor Digitorum Communis (EDC) presented as mean $\pm$ SE. EMG values obtained in a
630 preliminary study performed with five subjects using a joystick-like handle are reported for
631 comparison. (*: $p < 0.05$ (maximum); °: $p < 0.05$ (mean))

632

633

634 Figure 7: Mean $\pm$ standard deviation of the questionnaire data. For each criterion, the linear
635 scales reach from 0-10 (Comfort: 0 = “uncomfortable”, 10 = “comfortable”; Fatigue: 0 = “no
636 fatigue”, 10 = “severe fatigue”; Task difficulty: 0 = “very easy”, 10 = “very difficult”; Pain: 0 =
637 “no pain”, 10 = “severe pain”). * $p < 0.05$

Muscle pair		FCR - ECR	FCR - FDS	ECR - EDC	FDS - EDC
CI Values 0 -100%: F-value (p-value)					
Within-subjects effect F(2,16)		3.968 (p=0.040)	5.717 (p=0.013)	0.412 (p=0.669)	1.117 (p=0.352)
<i>Post-hoc</i>					
Curved - Grooved		1.000	1.000	-	-
Curved - Palm		0.412	0.103	-	-
Grooved - Palm		0.048	0.108	-	-
CI Values 10 -30%: F-value (p-value)					
Within-subjects effect F(2,16)		1.209 (p=0.324)	5.748(p=0.013)	0.892 (p=0.429)	1.648 (p=0.223)
<i>Post-hoc</i>					
Curved - Grooved		-	1.000	-	-
Curved - Palm		-	0.036	-	-
Grooved - Palm		-	0.106	-	-
CI Values 70 -90%: F-value (p-value)					
Within-subjects effect F(2,16)		3.305 (p=0.063)	1.533 (p=0.246)	0.557 (p=0.583)	2.962 (p=0.080)
Comparison of CI values for the joystick-like handle: p-values					
Curved handle	entire trial	0.203	0.831	0.792	0.032
	10-30% of trial	0.138	0.763	0.982	0.036
	70-90% of trial	0.006	0.006	0.331	0.018
Grooved handle	entire trial	0.270	0.661	0.789	0.085
	10-30% of trial	0.089	0.236	0.756	0.096
	70-90% of trial	0.014	<0.001	0.410	0.091
Palm handle	entire trial	0.028	0.237	0.833	0.042
	10-30% of trial	0.009	0.296	0.715	0.070
	70-90% of trial	<0.001	<0.001	0.681	0.004

638

639 Table 1: F-values and p-values for the repeated measure ANOVA analyzing the co-activation
640 index (CI) values for different muscle pairs including the muscles Flexor Carpi Radialis
641 (FCR), Extensor Carpi Radialis (ECR), Flexor Digitorum Superficialis (FDS) and Extensor
642 Digitorum Communis (EDC). Post-hoc analysis is reported when within-subject effect was
643 significant. Bottom part of the table shows the results of the t-test comparing the three
644 handles (curved, grooved, palm) to the joystick-like handle used in a previous study.

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Muscle		FCR	ECR	FDS	EDC
Normalized EMG 0 -100% F-value (p-value)					
Within-subjects effect F(2,16)					
<i>maximum value</i>		2.516 (p=0.112)	2.776 (p=0.129) ¹	1.792 (p=0.198)	2.418 (p=0.121)
<i>mean value</i>		1.451 (p=0.263)	3.474 (p=0.090) ⁴	1.124 (p=0.349)	2.121 (p=0.152)
Normalized EMG 10 -30% % F-value (p-value)					
Within-subjects effect F(2,16)					
<i>maximum value</i>		2.594 (p=0.106)	2.080 (p=0.157)	1.853 (p=0.189)	2.647 (p=0.102)
<i>mean value</i>		2.213 (p=0.142)	2.027 (p=0.164)	2.011 (p=0.166)	3.044 (p=0.076)
Normalized EMG 70 -90% % F-value (p-value)					
Within-subjects effect F(2,16)					
<i>maximum value</i>		0.264 (p=0.654) ²	2.993 (p=0.115) ³	0.062 (p=0.940)	2.923 (p=0.083)
<i>mean value</i>		0.314 (p=0.629) ⁵	2.957 (p=0.119) ⁶	0.209 (p=0.814)	2.833 (p=0.088)
Comparison to joystick-like handle: p-values					
Curved handle	<i>maximum value 0-100%</i>	0.309	0.039	0.004	0.028
	<i>mean value 0-100%</i>	0.041	0.031	<0.001	0.007
	<i>maximum value 10-30%</i>	0.332	0.107	0.003	0.008
	<i>mean value 10-30%</i>	0.351	0.061	0.004	0.008
	<i>maximum value 70-90%</i>	0.025	0.010	0.004	0.022
	<i>mean value 70-90%</i>	0.016	0.004	0.014	0.010
Grooved handle	<i>maximum value 0-100%</i>	0.388	0.481	0.146	0.301
	<i>mean value 0-100%</i>	0.231	0.293	0.004	0.057
	<i>maximum value 10-30%</i>	0.590	0.484	0.151	0.039
	<i>mean value 10-30%</i>	0.881	0.334	0.076	0.029
	<i>maximum value 70-90%</i>	0.086	0.227	0.005	0.244
	<i>mean value 70-90%</i>	0.051	0.145	0.004	0.103
Palm handle	<i>maximum value 0-100%</i>	0.787	0.018	0.468	0.013
	<i>mean value 0-100%</i>	0.117	0.010	0.021	0.002
	<i>maximum value 10-30%</i>	0.848	0.024	0.520	0.042
	<i>mean value 10-30%</i>	0.950	0.013	0.518	0.042
	<i>maximum value 70-90%</i>	0.009	0.005	0.002	<0.001
	<i>mean value 70-90%</i>	0.007	0.002	0.003	<0.001

¹ GH: F(1.118, 8.948), ² GH: F(1.163, 9.303), ³ GH: F(1.130, 9.039), ⁴ GH: F(1.175, 9.403), ⁵ GH: F(1.2, 9.598) ⁶ GH: F(1.102, 8.817)

Table 2: F-values and p-values for the repeated measure ANOVA analyzing the maximal and mean normalized EMG values for the different muscles Flexor Carpi Radialis (FCR), Extensor Carpi Radialis (ECR), Flexor Digitorum Superficialis (FDS) and Extensor Digitorum

652 Communis (EDC). Greenhouse-Geisser (GH) adjustment is reported at the bottom if it was
653 applied due to violation of sphericity. Bottom part of the table shows the results of the t-test
654 comparing the three handles (curved, grooved, palm) to the joystick-like handle used in a
655 previous study.

656

Figure 1

Figure 2

Figure 3

— Curved handle — Grooved handle — Palm handle — Minimal Jerk

Figure 4

Flexor Carpi Radialis

Extensor Carpi Radialis

Flexor Digitorum Superficialis

Extensor Digitorum Communis

B **C**

Figure 5

FCR – ECR

FCR – FDS

FDS – EDC

ECR – EDC

Figure 6**Flexor Carpi Radialis** **Extensor Carpi Radialis** **Flexor Digitorum Superficialis** **Extensor Digitorum Communis**

Figure 7